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Magnetic local time dependence of geomagnetic disturbances contributing to the AU and AL indices

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Abstract. The Auroral Electrojet (AE) indices, which are composed of four indices (AU, AL, AE, and AO), are calculated from the geomagnetic field data obtained at 12 geomagnetic observatories that are located in geomagnetic latitude (GMLAT) of 61.7°–70°. The indices have been widely used to study magnetic activity in the auroral zone. In the present study, we examine magnetic local time (MLT) dependence of geomagnetic field variations contributing to the AU and AL indices. We use 1-min geomagnetic field data obtained in 2003. It is found that both AU and AL indices have two ranges of MLT (AU: 15:00–22:00 MLT, ∼06:00 MLT; and AL: ∼02:00 MLT, 09:00–12:00 MLT) contributing to the index during quiet periods and one MLT range (AU: 15:00–20:00 MLT, and AL: 00:00–06:00 MLT) during disturbed periods. These results are interpreted in terms of various ionospheric current systems, such as, S_q^p, S_q, and DP2.

Keywords. Magnetospheric physics (Auroral phenomena; Storms and substorms)

1 Introduction

The Auroral Electrojet (AE) indices were originally introduced by Davis and Sugiura (1966) as a measure of global electrojet activity in the auroral zone. After the initial development at the NASA/Goddard Space Flight Center, the calculation of the index was first performed at the Geophysical Institute of the University of Alaska, which published hourly values of the index for the years 1957 to 1964. The production of 2.5 min values was then made at the Goddard Space Flight Center for the period from September 1964 to June 1968. After these early publications the index was regularly issued by the World Data Center A for Solar-Terrestrial Physics (WDC-A for STP) in Boulder, Colorado, which published 2.5 min values for the years 1966 to 1974 and 1.0 min values for 1975 and the first 4 months of 1976. When it became difficult for the WDC-A for STP to continue the production of the AE index, the WDC-C2 for Geomagnetism, which is operated by the Data Analysis Center for Geomagnetism and Space Magnetism, Faculty of Science, Kyoto University, took over the job and started to produce the AE index from the International Magnetospheric Study period (1978–1979). Since then, WDC-C2 for Geomagnetism (renamed WDC for Geomagnetism, Kyoto after 2000) has been publishing 1.0 min values of the AE indices.

At present, the AE indices are derived from geomagnetic variations in the H (horizontal) component observed at selected 12 observatories along the auroral zone in the Northern Hemisphere. (Note that the original paper by Davis and Sugiura (1966) adopted 7 observatories.) First, a base value for each station is calculated for each month by averaging all the data from the station on the five international quietest days. This base value is subtracted from each value of 1-min data obtained at the station during that month, resulting in ΔH. (Also note that hourly values or 2.5-min values were used before 1974.) Then among the ΔH values from all the stations at each given UT time, the largest and smallest values are selected. The AU and AL indices are respectively defined by the largest and the smallest values so selected. The symbols, AU and AL, derive from the fact that these values form the upper and lower envelopes of the superposed plots of all the data from these stations as functions of UT. The difference,

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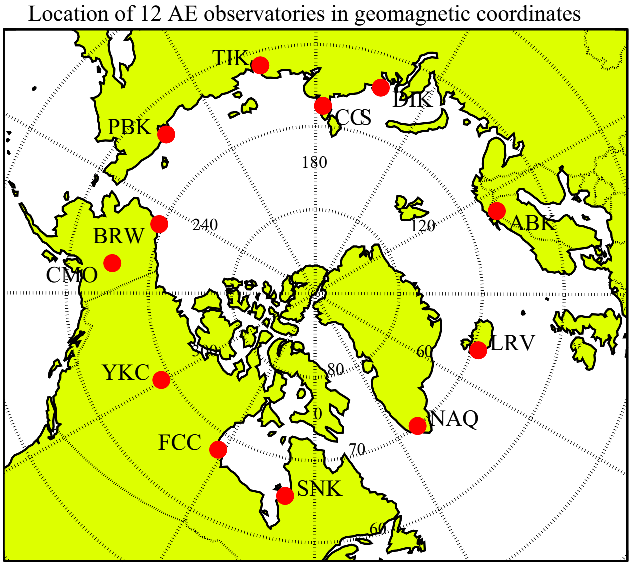

Fig. 1. Location of the current AE observatories in geomagnetic coordinates. Latitude circles are drawn at 10° intervals and longitude are separated by 30° intervals.

AU minus AL, defines the AE index, and the mean value of the AU and AL, i.e. (AU + AL)/2, defines the AO index. The term "AE indices" is usually used to represent these four indices (AU, AL, AE, and AO). The AU and AL indices are intended to express the strongest current intensity of the eastward and westward auroral electrojets, respectively. The AE index represents the overall activity of the electrojets.

It is of interest to examine which station (or what magnetic local time (MLT)) contributes most to the AU and AL indices. Davis and Sugiura (1966) showed that the AU and AL indices during disturbed interval mostly reflect variations at 14:00–21:00 MLT and 23:00–05:00 MLT, respectively. Allen and Kroehl (1975) found that during disturbed intervals, stations located from the duskside to the postmidnight make AU and AL variations and their contributing peak times are around 17:45 MLT for AU and 03:15 MLT for AL. During quiet times, stations in the sunlit hemispheres additionally contribute to low-amplitude AU and AL indices and their peak contribution is from 06:15 MLT for AU and 11:15 MLT for AL. In these previous studies, the number of the AE observatories was less than 12 (i.e., 7 and 11, respectively) and the time resolution is larger than 1 min (i.e., 2.5-min), both of which are not relevant to the present AE index derivation. Therefore, in the present study, using the 1-min data from the 12 AE observatories, we intend to investigate what MLT contributes to the AU and AL indices. Moreover, after the paper by Allen and Kroehl (1975) was published, more than 35 years have passed; and the number of reseachers using the AE index has been increasing because the real time AE index has become available from http://wdc.kugi.kyoto-u.ac.jp/ae_realtime/index.html. Thus we think it is worth revisiting this issue. Since the current system in the polar ionosphere is expected to be different during quiet and disturbed periods, we separately examined the MLT dependence of contribution for each period. The paper is organized as follows. In Sect. 2, we present fundamental information of the AE stations. In Sect. 3, we show the frequency of contribution to the AU and AL indices for each station in quiet and disturbed periods. We also display the MLT dependence of the ΔH values for each station. Discussion and summary are given in Sects. 4 and 5.

2 Data set

Figure 1 shows the location of the present 12 AE observatories in geomagnetic coordinates. We can see that the AE observatories are located in 61.7°–70°geomagnetic latitude (GMLAT), called the auroral zone or the sub-auroral zone; and they are separated by 15°–48°in geomagnetic longitude (GMLON). Table 1 compiles the IAGA code, GMLAT, GMLON, the status, and the institute responsible for the operation of the present/previous AE stations. Some AE stations have closed and were replaced with a new observatory. For example, Great Whale River (GWR) was closed in July 1984, and Poste-de-la-Baleine (PBQ) took over it from September 1984. But PBQ was closed in November 2007, and Sanikiluaq (SNK) is alternatively working now. Similarly, Cape Wellen (CWE) was closed in 1996 and replaced with Pebek (PBK) in April 2001. In this study, we use 1-min geomagnetic field data obtained in 2003, in which all 12 observatories were operated in good shape. Therefore, this study uses data not from SNK (current station) but from PBQ (previous station). As seen from Table 1, these two stations are very close to each other, leading us to believe that results in the present study hold for the recent AE indices using the SNK data.

3 MLT dependence of geomagnetic field variations in quiet and disturbed periods

3.1 Quiet periods

Here, quiet period is defined as a period of AE $<$100 nT. During the selected quiet periods, the 1-min ΔH values are compared among the 12 AE observatories at a given UT time, and we identify which 2 stations contributed to the AU and AL indices, respectively. Then we count the number of the 1-min ΔH values contributing to AU (N_{AU}) and AL (N_{AL}) in 1-h UT bins for each station. Results are shown in Fig. 2a; left panel is for AU and right panel is for AL. N_{AL} and N_{AU} are indicated with small dots. A vertical division between observatories corresponds to 5000 1-min ΔH values. We calculate a frequency of contributing to the AU and AL indices (f_{AU} and f_{AL}), which is defined as $N_{\mathrm{AU}}/N_{\mathrm{total}}$ and $N_{\mathrm{AL}}/N_{\mathrm{total}}$, respectively, where N_{total} is the total number of the 1-min ΔH

Table 1. List of the present 12 AE stations. Stations above (below) the double line are currently working stations (previous stations). Values of geomagnetic coordinates are given for January 1, 2003 by using the IGRF-11 geomagnetic field model.

Observatory	IAGA code	GMLAT[°]	GMLON[°]	Status	Source[a]
Abisko	ABK	66.04	114.76	Operating	GSS
Dixon Island	DIK	63.97	162.53	Operating	AARI
Cape Chelyuskin	CCS	67.04	177.78	Operating	AARI
Tixie Bay	TIK	61.69	193.63	Operating	AARI
Pebek	PBK	63.75	223.15	Opened in 2001/04	AARI
Barrow	BRW	69.52	245.94	Operating	USGS
College	CMO	65.36	261.42	Operating	USGS
Yellowknife	YKC	68.89	299.27	Operating	GSC
Fort Churchill	FCC	68.03	328.16	Operating	GSC
Sanikiluaq	SNK	66.71	349.52	Opened in 2007/12	GSC
Narsarsuaq	NAQ	70.03	37.98	Operating	DTU
Leirvogur	LRV	69.35	71.15	Operating	UI
Great Whale River	GWR	65.52	351.64	Closed in 1984/07	GSC
Cape Wellen	CWE	62.83	241.16	Closed in 1996	AARI
Poste-de-la-Baleine	PBQ	65.52	351.64	Opened in 1984/09 Closed in 2007/11	GSC

[a] GSS: Geological Survey of Sweden, AARI: Arctic and Antarctic Research Institute, USGS: US Geological Survey, GSC: Geological Survey of Canada, DTU: DTU Space, National Space Institute, Technical University of Denmark, UI: University of Iceland.

values in 1-h bins for each station. f_{AU} and f_{AL} are displayed with orange and blue shading in Fig. 2a. A vertical division between observatories corresponds to 100%. A black circle represents geomagnetic local midnight at each station and a white circle represents geomagnetic local noon. From left panel of Fig. 2a, we can find that there are possibly two broad MLT ranges within which the AU index is determined. A primary MLT range is found on duskside and a secondary MLT range appears near dawnside, in particular, in YKC, BRW, and DIK. For the AL index, we can also see two broad MLT ranges centered around postmidnight and around geomagnetic local noon.

Figure 2b shows MLT dependence of average values of ΔH, which are calculated over 15 min intervals of MLT. Results are indicated by colors of annulus placed in a descending order of the GMLAT from the center, that is, for NAQ, BRW, LRV, YKC, FCC, CCS, ABK, PBQ, CMO, DIK, PBK, and TIK from the center. Outer and inner circles represent 60° GMLAT and 70° GMLAT, respectively; thus scales in Fig. 2b are different between 60°–70° and >70°.

We find that ΔH has two MLT ranges showing broad positive peaks on the duskside (15:00–22:00 MLT) and the dawnside (∼06:00 MLT). For the peak on the duskside, peak MLT at higher GMLAT stations are about a few hours earlier than that at lower stations, and ΔH values are generally larger at higher GMLAT stations. The dawnside peak is less clear, and not all AE stations show peaks. We also find that ΔH shows negative peaks around postmidnight (∼02:00 MLT) and local noon (09:00–12:00 MLT). The postmidnight troughs can be seen in almost all stations except CMO. The local noon troughs appeared in all stations, and ΔH seems larger than that of the postmidnight trough.

3.2 Disturbed periods

In the similar manner to the quiet period, we investigate the number of the 1-min ΔH values contributing to the AE indices for disturbed periods, which is defined by a period of AE >200 nT. In such periods, the ionospheric current system is thought to be different from that in quiet periods and mainly associated with substorms and storms (e.g., Fukushima, 1953; Akasofu et al., 1965; Nishida, 1968). Figure 3a shows N_{AU} and f_{AU} (left panel) as well as N_{AL} and f_{AL} (right panel) for the disturbed period in 2003. A vertical division between observatories corresponds to 10 000 1-min values or 100%. From this figure, we can find an only broad time range of MLT, within which each station contributes to the AE indices. Peak MLT is centered around duskside for the AU index and around postmidnight for the AL index. Figure 3b shows the MLT dependence of average values of ΔH for disturbed period. ΔH shows broad MLT ranges of a peak at 15:00–20:00 MLT and a trough at 00:00–06:00 MLT.

4 Discussion

4.1 Quiet periods

It was reported in previous studies that the ionospheric current system during quiet period is mainly composed of the S_q current system and the S_q^p current system. The S_q current

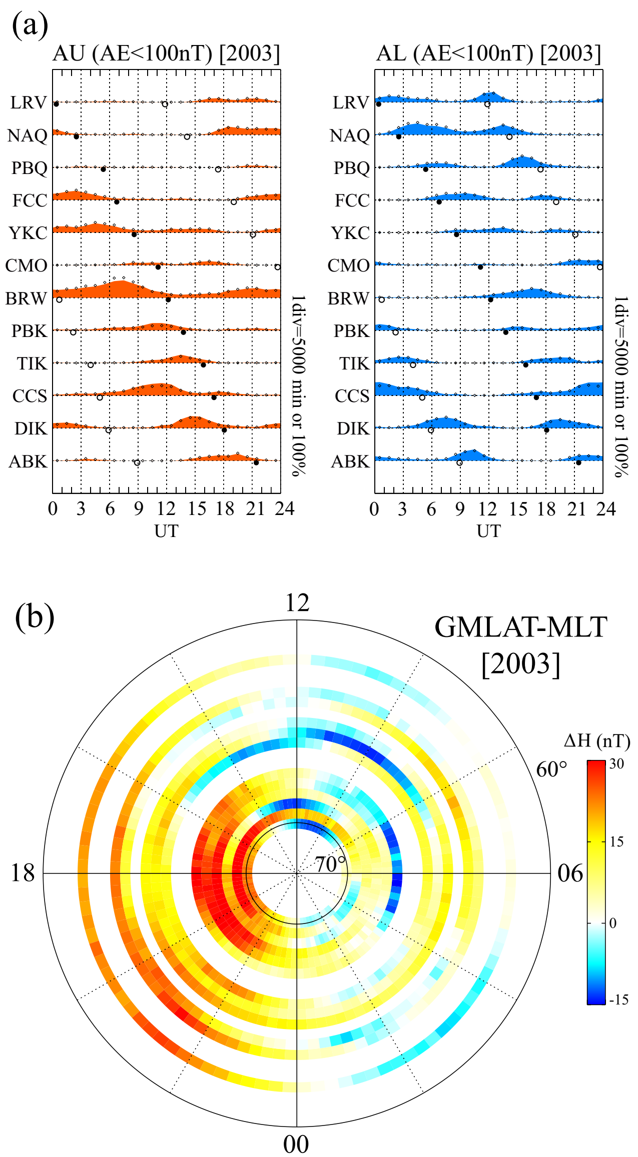

Fig. 2. MLT dependence of geomagnetic field variations in quiet periods, that is, AE <100 nT. **(a)** The number of the 1-min ΔH values contributing to AU and AL in 1-h UT bins (small dots), and a frequency of contributing to the AU and AL indices (orange and blue shading). Black and white circles represent geomagnetic local midnight and geomagnetic local noon at each station. **(b)** Average values of ΔH calculated over 15 min intervals of MLT for each observatories.

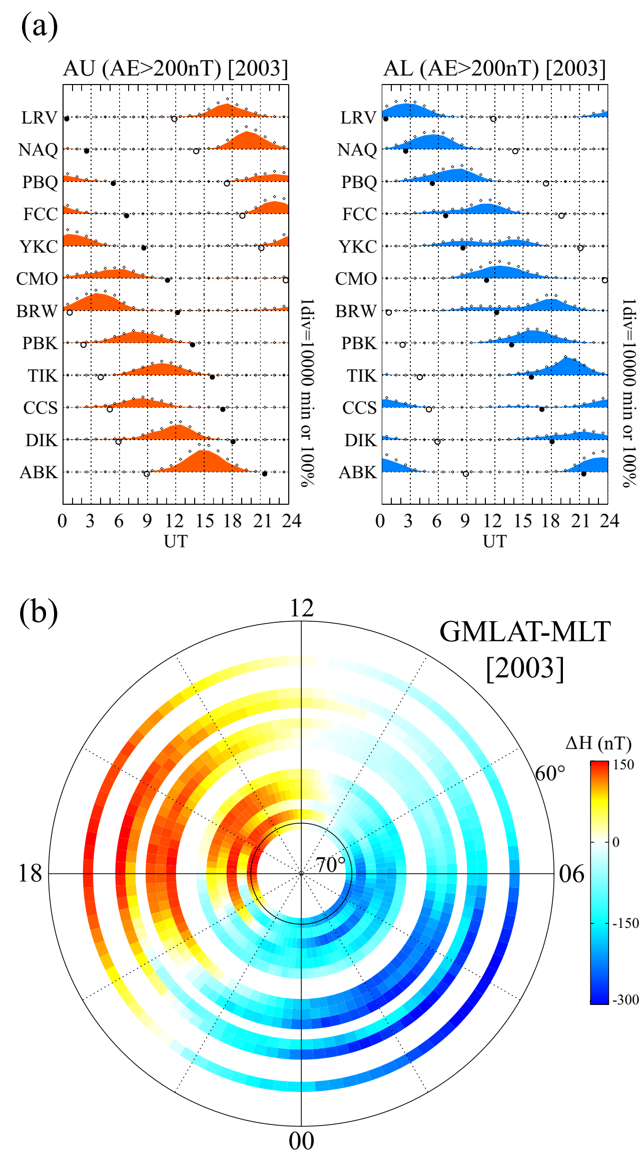

Fig. 3. Same as Fig. 2, but for the disturbed periods, that is, AE >200 nT.

system is generated by the dynamo effects in the ionosphere associated with heating by solar radiation, and appears over wide latitudinal range in the sunlit hemisphere (e.g., Vestine et al., 1947). The current in the Northern Hemisphere flows anti-clockwise. The S_q^p current system is dominant in the polar region and described by the twin-vortex currents located in both the dawn and dusk sides (e.g., Nagata and Kokubun, 1962). Generally, the current flows from the dayside to the nightside around 60°–75°GMLAT and connects to the trans-polar sunward current.

Because of these current systems, the AE stations located at 61°–70° GMLAT observe daily variations of ΔH during the quiet period. The expected geomagnetic variations are depicted in Fig. 4a. The S_q current will create a negative variation around the local noon, and the S_q^p current will make a positive variation on the duskside as well as a negative variation around the dawnside, resulting in the total daily variations as shown in the bottom plot. In calculation of ΔH, the base value should be subtracted from the geomagnetic variations (see Sect. 1). For the $S_q$variation, the base value becomes negative, which is indicated by a dotted horizontal line in Fig. 4a, whereas the S_q^p variation has zero base

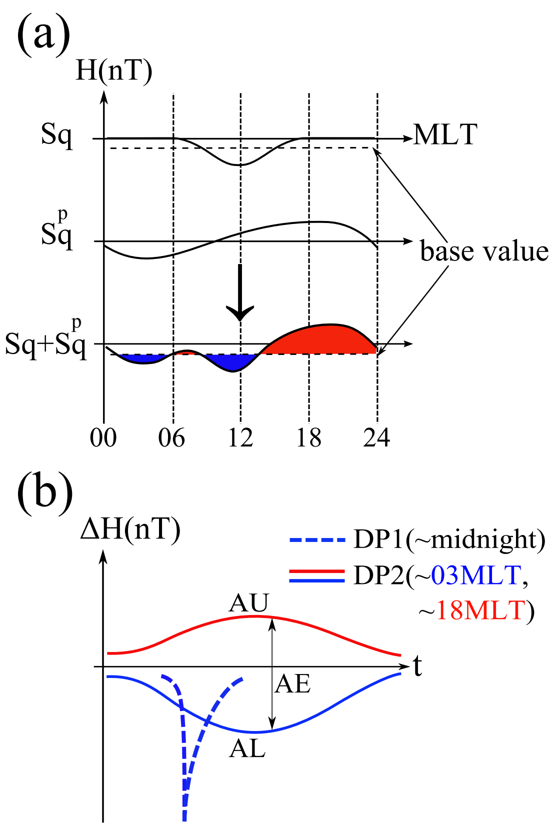

Fig. 4. (a) Expected MLT dependence of geomagnetic variations in quiet periods, which are composed of the S_q and S_q^p current systems. **(b)** Expected temporal changes of geomagnetic field in disturbed periods, which are composed of the DP1 and DP2 current systems.

value. As a result, the total daily variations also have a negative base value. Therefore, the calculated ΔH is expected to show MLT dependence as indicated with red for positive values and blue for negative values. In addition, we should consider the latitudinal dependence of the geomagnetic field variations. It is expected that geomagnetic field variations in the higher latitude are stronger than that of the lower latitude because the S_q^p current system mainly flows in the polar ionosphere of $\geq$65° GMLAT (e.g., Nagata and Kokubun, 1962).

This MLT and latitudinal dependence of ΔH are consistent with the results found in Fig. 2. We conclude that the positive peak around 15:00–22:00 MLT and the negative peak at ~02:00 MLT are attributed to the S_q^p current system; and the negative peak around 09:00–12:00 MLT are due to the S_q current system. From the bottom trace of Fig. 4a, we suppose that the weak positive peak found at ~06:00 MLT is seemingly created and it is not an evidence of eastward current.

We performed the same analyses for the other criteria of quiet periods such as $-50\,\text{nT} > \text{AL} > -100\,\text{nT}$, $\text{AL} > -50\,\text{nT}$ and found that results are not essentially changed.

4.2 Disturbed periods

During the disturbed period, the DP1 and DP2 current systems predominate over the S_q and S_q^p current systems. The DP1 current system is related to substorms and consists of strong westward auroral electrojet (e.g., Fukushima, 1953; Akasofu et al., 1965). The DP2 current system reflects the time variability of the global magnetospheric convection and is closely correlated with IMF (Nishida, 1968). The current pattern is similar to S_q^p but extends much lower in latitude.

Figure 4b illustrates temporal changes of ΔH in the auroral latitude expected from these current systems. Since the DP1 current system is enhanced at substorms, a negative ΔH appeared in only short time period, as shown with a dotted blue curve. The DP2 current system creates both positive ΔH on the duskside (solid red curve) and negative ΔH on the dawnside (solid negative curve).

From Fig. 3, we find the positive ΔH around 15:00–20:00 MLT and the negative ΔH around 00:00–06:00 MLT. One may raise a question why ΔH showed no clear negative values at premidnight, where auroral breakups are initiated, because the AL index is often used as a signature of substorms. We consider that this is because of short duration of the DP1 current system. It should be noted that the AE indices during disturbed periods includes two components: DP1 and DP2. Since the duration of DP1 is shorter than DP2 (Fig. 4b), the effect of DP1 is masked by that of DP2 in the statistical analysis. Thus, we conclude that the ΔH found in Fig. 3 mainly reflects the DP2 current system (e.g., Nagata and Kokubun, 1962; Nishida et al., 1966). In general, the ionospheric current system of DP2 statistically shows dawn-dusk asymmetry in its shape, that is, the afternoon cell often expands in dawnward at the dayside. The same signature is also seen in Fig. 3a. The boundary between positive (red) and negative (blue) of ΔH variation is located at near 11 MLT. This fact supports our interpretation. We expect that the effect of the DP1 current system will become apparent if we define the disturbed period such that the AE index shows sudden increases, for example, $\text{dAE/dt} > 100\,\text{nT}\,\text{min}^{-1}$. This is left for future studies.

We performed the same analyses for the other criteria of disturbed periods such as $\text{AL} < -200\,\text{nT}$, $\text{AE} > 400\,\text{nT}$ and found that results are essentially identical.

5 Summary

Though the number of researchers using the AE indices has been increasing recently, there have not been studies investigating basic features of the AE indices for a long time since the work of Allen and Kroehl (1975). Then we re-examine MLT dependence of geomagnetic field variations contributing to the AU and AL indices, using the 1-min geomagnetic field data obtained at 12 observatories. It is found that both AU and AL indices have two ranges of MLT (AU: 15:00–22:00 MLT, ~06:00 MLT; and AL: ~02:00 MLT, 09:00–12:00 MLT) contributing to the index during quiet periods and one MLT range (AU: 15:00–20:00 MLT, and AL: 00:00–06:00 MLT) during disturbed periods. These results can be interpreted in terms of various ionospheric current systems, such as, S_q^p, S_q, and DP2. We should bear in mind these results when we use the AE indices.

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